CRETACEOUS AND CENOZOIC HISTORY OF THE NORTHERN CONTINENTS

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The dispersal and migration of terrestrial plants and animals are controlled to a large extent by the distribution of land, sea, and orographic features and by climate. All these factors in turn are controlled in substantial part by the motions of the great plates that comprise the earth's outer shell, its lithosphere. Continents stand above sea level because of their thick, light crust, but they are parts of plates that also include the ocean floors. Seven very large plates, and numerous mid- and small-sized ones (the concept of coherent plates breaks down at the small-scale end), each typically 80 km or so thick, all move relative to all others. The plates tend to be internally rigid, and they interact mostly at their edges, although large, mostly continental parts of some plates undergo severe internal deformation. Velocities of relative motion between adjacent plates range upward to about 13 cm/year—an unimposing rate by human standards, but equivalent to enormous displacements when continued for tens of millions of years.

Spherical geometry requires that any motion between two parts of a spherical surface can be expressed as the rotation of one part relative to the other, defined by an angular displacement around an Euler pole of relative rotation. All trajectories of relative motions must be along small circles to that pole. (This pole is not to be thought of as having any mechanical significance.) The development of plate-tectonic concepts in the late 1960s was made possible by the demonstration that the relative motions that could be quantified fit these geometric requirements. The mechanisms causing plate motions are much debated, but the reality of the motions is proved.

Plates are now pulling apart primarily along the great submarine ridges in the world's oceans. As mantle wells up into the gaps between diverging plates at these spreading centers, part of it melts and is erupted on the surface as basaltic lava or is injected beneath the surface to crystallize as intrusive igneous rocks. The ridge stands high because its crust and mantle are hot, and hence are low in density. A steady state develops as the plates continue to move apart: the material at the ridge is hot when newly formed, but it cools and contracts as it migrates away, and the sea floor sinks to greater depths. The oceanic crust and upper mantle formed at spreading centers retain petrologic characteristics that can be recognized after subsequent events have brought them to other tectonic settings.

Where plates converge, one plate commonly tips down and slides beneath the other. Generally, an oceanic plate slides (subducts) beneath a continental plate (as along the west side of South America), or beneath another oceanic plate (as along the east side of the Mariana island arc). In either case, a magmatic arc—volcanoes at the surface, intrusive complexes at depth—tends to form in that part of the overriding plate that is about 100 km above the top of the subducting plate. Compositions of the magmatic rocks are quite different in continental and oceanic arcs. Sediments and other materials scraped off the top of the downgoing plate accumulate, snowplow fashion, in an accretionary wedge at the front of the overriding plate. Study of an accretionary wedge can reveal much about the character and history of oceanic lithosphere that has been subducted beneath the overriding plate.

Collisions result where light crustal masses are present on both of two converging plates, and any accretionary-wedge material is caught in the suture between the two. Collisions are often accompanied by severe internal deformation of one or both of such plates. Convergence commonly continues after a collision, but inasmuch as subduction of buoyant continental crust is difficult or impossible, subduction stops at the old site at which oceanic lithosphere had previously been subducted, and a new subduction system breaks through on the outer side of the continent as enlarged by the aggregation of the collided ma-

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terial. Actual collisions are commonly oblique rather than head-on, and they progress in one direction or another with time.

Strike-slip faults bound plates that slide past one another. Any strike-slip fault transfers spreading or convergence at one end to spreading or convergence at the other end. Many actual strike-slip boundaries are complex in detail and have obliquely convergent and divergent parts and also zones of distributed motion.

Plate motions are often illustrated by two-dimensional cartoons, many of which incorporate the false concept that the subducting plate is rolled over a platen fixed in the mantle and is injected down a fixed slot. All or most hinges actually migrate into the subducting plates as the overriding plates advance. Boundaries between adjacent plates tend to end at triple junctions, where three plates meet; such areas can display great variety and complex evolutions.

I have summarized the evidence for, and evolution of, these concepts elsewhere and have illustrated the development of a number of actual convergent-plate features (Hamilton, 1979).

Plate tectonics has operated throughout at least the last 2,500 million years—all of Proterozoic and Phanerozoic time. Continental rifting is recorded by truncations of basement terranes and by the deposition on the truncated margins of continental-shelf-and-slope stratal wedges. Subduction of oceanic lithosphere is recorded by most of the same structural and magmatic indicators that characterize modern tectonic systems; by aggregations through collisions of distinct continental masses and island arcs; and by paleomagnetic, paleoclimatic, and paleontologic indicators. The details of the processes, however, have changed with time. Thus, most of the earth's potassium had been cycled out of the mantle and into the continents before Paleozoic time; Phanerozoic granitic rocks are both voluminous and potassic only where their magmas have risen through Precambrian crust, or through voluminous sediments derived from such crust. Metamorphic rocks of blueschist facies, products of recrystallization at high pressures but relatively low temperatures within subduction systems, are voluminous in Mesozoic and Cenozoic terranes, progressively less common in older Paleozoic ones, rare in late Proterozoic terranes, and unknown in older tracts; the earth probably is cooling and losing heat at a progressively decreasing rate. Surface temperatures, however, are determined primarily by the sun, and they have not varied widely within the last 3,800 million years—the age of the oldest rocks known—for liquid water has always been present, and continental glaciation has occurred intermittently during the last 2,000 million years at least.

During Archean time, 2,500 to 3,800 million years ago (Ma), continents were formed by magmatism more intense than that of later time, in ways that are much disputed, but that many of us regard as the result of rapid motions of small lithosphere plates. Even then, however, the earth must have lost heat primarily through spreading oceans and by subduction-related magmatism, because the crustal geothermal gradients recorded by petrologic indicators in deeply eroded Archean rocks are much like those in young terranes. Before 3,800 Ma, whatever crust the earth possessed was so thin, and destructive (remelting?) processes were so effective, that no rocks then formed have been recognized.

No beginning in time can be seen for plate motions. The earth's lithosphere has always consisted of rifting, drifting, subducting, and colliding plates. All continents are aggregates of fragments, sutured together at times past. Continents have been deformed complexly by strike-slip faulting and by oblique and orthogonal rifting and compression, and the process continues. Reconstructions of prior positions of land masses become progressively more ambiguous as the age considered increases. Although valiant attempts have been made at reconstructions for all of Phanerozoic time (e.g., Smith et al., 1981, and Ziegler et al., 1979) and even for the late Precambrian, such reconstructions ignore most pre-Jurassic sutures and continental deformation, are constrained primarily by approximate latitudes inferred for some of the bits, and are schematic at best. Even for Cretaceous time, major uncertainties exist regarding the geometry of eastern Siberia and Alaska; of the entire Tethyan region (Central America, Caribbean, Mediteranean, Alpine Europe, North Africa, middle East, Himalayas, Southeast Asia, Indonesia, Melanesia); of onshore and offshore East Asia; and of the Scotia-West Antarctica region. Many of the ambiguities are more likely to be resolved by paleobiogeographic studies than by geologic and geophysical ones.

The biogeographic consequences of plate motions and interactions must be enormous. For example, a small landmass on a moving plate can carry a terrestrial biota derived partly from a biota shared with some previously adjacent landmass, and derived partly by fortuitous immigration, both components evolving more or less in isolation as the landmass moves with time through different climatic zones. The configuration and surface altitude and, hence, the amount and distribution of land above sea level, can change radically with time. When two landmasses collide, their biotas mingle and compete. Pre-collision fossil biotas of the two lands are different, whereas post-collision biotas are shared.

This paper briefly summarizes some tectonic factors that may be relevant to the biotic relationships of the northern continents during Cretaceous and Cenozoic time. Little mention is made of the biotic features themselves.

North American and Eurasian Plates

North America north of Mexico, and Eurasia north of the Alpine-Himalayan mountain system, behaved as internally coherent continental plates during Cretaceous and Cenozoic time, although they had complex histories of pre-Cretaceous sundering and aggregation, and although they were much deformed internally during the Cretaceous and Cenozoic. The two megaplates began to separate in middle Cretaceous time, and the Atlantic Ocean has been widening ever since. Relationships between Siberia and North America throughout this time are poorly understood. The following presentation is concerned with some internal and marginal features of the two megaplates, and not with relationships between the megaplates.

NORTH AMERICAN PLATE

Tectonic accretion of western North America. Much of the western part of the North American Cordillera consists of material added to the continent by subduction processes during Jurassic and Cretaceous time, and to a lesser extend during Cenozoic time. Alaska (e.g., Jones & Silberling, 1979), southwest Yukon Territory and the southwestern two-thirds of British Columbia (e.g., Tipper et al., 1981), and most of Washington, Oregon, and western California (e.g., Hamilton, 1978) consist largely of continental fragments, island arcs, and assorted debris scraped off oceanic lithosphere plates, and of magmatic rocks formed in response to subduction and to rifting. Paleontologic and paleomagnetic evidence requires that some of these materials were conveyor-belted many thousands of kilometers to their present North American sites. The aggregate width of the accreted materials generally increases northwestward along the continental margin, from 50 to 100 km (much of that offshore) in Baja California and southern California, through 500 km in Washington and Canada, to 1,000 km in Alaska. Throughout Cretaceous and Cenozoic time, the oceanic and continental-margin materials have had northward components of motion relative to interior North America, whether the specific motion has recorded oblique subduction, oblique extension, or strike-slip.

All the fragments of continental materials presumably carried significant biotas if they stood above the sea before collision, but none is known to have been other than a briefly detached bit of North America. Conversely, the fragments for which distant origins are likely are largely of submarine origin, although some may have included small islands before collision. I know of no biotic interchanges that can be ascribed to the accretion of any of the fragments, although juxtaposed fossil assemblages are grossly disjunct in many places.

Western Interior seaway. The Western Interior of the United States and Canada—a region that is now at generally high surface altitude in such provinces as the High Plains, Colorado Plateau, and much of the U.S. Rocky Mountains—was inundated by a shallow sea that connected the Gulf of Mexico and the Beaufort Sea during middle Cretaceous time (McGookey et al., 1972; Rudkin, 1966; Williams & Burk, 1966). Seas transgressing south from the Arctic and north from the Gulf of Mexico joined in late Albian (latest Early Cretaceous) time, and the seaway remained more or less continuous until about early Campanian (middle Late Cretaceous) time. There was then widespread regression of the sea in Canada, but the Western Interior of the United States remained broadly inundated through most of the rest of Late Cretaceous time. The middle Cretaceous seaway was continuous between the Gulf of Mexico and the Canada Basin of the Arctic Ocean and must have much hindered east-west migration of terrestrial organisms. Cenozoic marine flooding of the continental margins was relatively minor.

Central America-Gulf of Mexico-Caribbean Sea. From the end of Triassic time until late in Pliocene time, North and South America were separated by water, although tectonic and volcanic lands may have connected them at times, and although continuity may have been maintained via Europe and Africa during much of Mesozoic time. The shapes and positions of landmasses within Mexico, Central America, and the Caribbean have changed greatly with time and are still only partly understood (Pindell & Dewey, 1982). Although subduction complexes have joined the continents at times, submarine gaps largely blocked migration of land organisms during Cretaceous and Tertiary time. The great intercontinental biotic interchange began only about three million years ago, when the Isthmus of Panama rose above sea level (Keigwin, 1978).

Internal deformation of North America. Alaska, western Canada, and the western United States were much deformed by lateral motions during Cretaceous and Cenozoic time. In addition to marginal tectonic accretion, an array of compressional, extensional, rotational, and strike-slip deformation (e.g., Hamilton, 1978) caused complex changes in orographic configurations, and hence much influenced climates, but did not produce any major seaway that would have impeded biotic interchanges.

Deformation in Eastern Canada, Greenland, and Alaska, is discussed in subsequent sections.

EURASIAN PLATE

Tectonic accretion of southern and eastern Eurasia. Eurasia is a composite megacontinent formed throughout Phanerozoic time by the aggregation of large and small subcontinents and of varied oceanic debris swept up between them, as intervening oceanic lithosphere was subducted (e.g., Burrett, 1974, and Hamilton, 1970). Northern sutures are in general older than southern ones. The land masses south of the Alps, Carpathians, Lesser Caucasus, and Himalayas have collided with Eurasia during Late Cretaceous and Cenozoic time (e.g., Burchfiel, 1980; Dewey et al., 1973; Sinha Roy, 1978). The accretion is still going on in both the west, where Africa and Arabia are in the process of closing with the northern continent, and in the east, where Australia has been colliding with island arcs migrating away from Asia (Hamilton, 1979). Continental masses have converged as intervening oceanic crust sank beneath one or both of them. Bits of continents have rifted, rotated, and re-aggregated. Island arcs have migrated, and changed their configurations, between converging continents. Shapes of colliding masses changed as they were crushed together.

Each of the arriving continental plates must have carried with it immigrant plants and animals and an assemblage of fossils—both different from those of the newly adjacent mainland. Thus, the middle Tertiary contact between Africa and Eurasia allowed horses to walk onto Africa and elephants onto Eurasia. Smaller islands must have carried limited biotas, evolved in varying isolation. Biotas were derived partly from the continent from which they rifted away; other biotas were derived partly from overwater immigrants. Thus, the middle Tertiary collision of Australia with island arcs that migrated from the margin of Asia caused much of the limited exchange of attenuated and variably evolved biotas between those two continents (Hamilton, 1979).

Seaways between Europe and Asia. During much of Late Jurassic and Early Cretaceous time and part of the early Tertiary, central Eurasia was covered by broad shallow seas that extended from the Tethyan ocean on the south to what is now the Arctic Ocean on the north (Grossheim & Khain, 1967; Vereshchagin & Ronov, 1968). During Late Jurassic and most of Early Cretaceous time, a seaway west of the Urals connected what are now the Caspian and Barents Sea regions. By late Early Cretaceous time (Albian, possibly also Aptian), the sea had receded from the northern part of this region, and dry land has connected the Russian Platform and the Urals ever since. East of the Urals, another broad, shallow sea transgressed southward during early Late Cretaceous (Cenomanian) time and covered what are now the West Siberian Lowlands through most of remaining Cretaceous, Paleocene, and Eocene time. Shallow seas also covered much of the Caspian-Aral region to the south, but between about 50° and 54° present latitude, northern and southern areas were separated by land, except that a more or less continuous seaway connected between northern and southern seas during most of Eocene time. Both eastern Russia and the West Siberian Lowlands were emergent in Oligocene and later time.

During much of the Early Cretaceous and again during most of the Eocene, marine water thus separated northern Europe and Siberia within what is now the USSR, although the sea may have regressed enough intermittently to provide land corridors between east and west. The Eocene seaway connected flooded continental shelves, beyond which were deep oceans, to the north and south, so migration of land biotas would have been severely hindered. The Early Cretaceous seaway similarly extended to deep ocean in the south and probably did so in the north also.

Internal deformation of Eurasia. South of about latitude 45° in Europe and 55° in Asia, Eurasia has been deformed by Cretaceous and Cenozoic extension, compression, and strike-slip motions, in addition to the accretion of land masses to the south and east margins of the continent (e.g., Alvarez et al., 1974; Burchfiel, 1980; Cohen, 1980; Dewey et al., 1973; Dewey & Sengor, 1979; Hamilton, 1979; Molnar & Tapponnier, 1975; Tapponnier & Molnar, 1979). Distribution and character of mountains, plateaus, basins, and deserts has changed complexly, but the general continuity of land in the main part of the continent, independent of accretion and rifting effects and the seaway just noted, has not.

OPENING OF THE ATLANTIC OCEAN

At about the end of Triassic time, North and South America, Africa, and western Europe were parts of a single large continent, the product of the suturing together of various lesser continents during Paleozoic time. Eastern Europe and Asia were bounded on the south by the broad Tethyan ocean. India and various lesser continental pieces of alpine Europe and the Middle East were not yet in contact with the northern continent. The subsequent opening of the North Atlantic is reasonably well constrained by the fitting together of ocean-floor magnetic anomalies (which are products of sea-floor spreading dated by deep-ocean drilling) and of the margins of continental crustal masses (Fig. 1). Following and accompanying tensional thinning of the continents along what became the Atlantic, North America plus Europe began to move northwestward away from Africa plus South America, in Middle Jurassic time, about 165 m.y.a. Europe and North America remained attached to one another; Iberia, at the southwest corner of the European plate, slid past Africa when the Atlantic opened beween the eastern United States and northwest Africa (Sclater et al., 1977). Simultaneously, the Gulf of Mexico, plus oceanic lithosphere since overridden by the eastward-expanding Caribbean plate, opened between the southern United States and South America. These motions continued until the end of Early Cretaceous time, about 95 Ma. The configuration of Central America and the Caribbean region during this time, and indeed during Late Cretaceous and early Tertiary time, is poorly constrained; continuous old continental lithosphere did not connect North and South America, but tectonic or volcanic lands may have joined them at times. Dry-land connections between the Americas, however, might have been maintained, at least intermittently, during Jurassic and Early Cretaceous time via Africa, Iberia, and western Europe.

The motion pattern changed greatly at about the beginning of Late Cretaceous time, and the Atlantic Ocean began to open; North and South America have been moving mostly westward since then, with little relative motion between them, away from Africa plus Europe. Sea-floor spreading was simple in the South Atlantic, and in the North Atlantic as far north as Newfoundland and Britain: the ocean widened steadily at the center, although at varying rates (Sclater et al., 1977).

PLATE BOUNDARIES BETWEEN THE ARCTIC AND ATLANTIC OCEANS

North of the latitude of Ireland, the spreading history of the Atlantic Ocean has been complex, patterns have changed with time, and transform faults have stepped spreading into the Arctic. Between the start of spreading in the middle Cretaceous and about 60 Ma in the Paleocene, spreading was concentrated west of Greenland, in the Labrador Basin; from about 60 to 38 Ma, spreading occurred both east and west of Greenland, although that to the west was very slow after about 50 Ma; since 38 Ma, spreading has taken place only east of Greenland (Jackson et al., 1979; Kristoffersen & Talwani, 1977; Sclater et al., 1977; Eldholm & Talwani, 1977; Vogt, Perry et al., 1981). Spreading between Norway and Greenland has jumped from rift to rift, and has not been confined to a single medial rift continuous in time.

ARCTIC ATLANTIC

The Arctic sector of the Atlantic Ocean—the Greenland and Norwegian Seas—opened as Greenland moved away from Norway. This spreading system ends at transform faults, along and southwest of the submerged continental margin of Spitsbergen and the Barents Shelf. These faults step the spreading into the Eurasian Basin of the Arctic Ocean, within which the spreading axis trends to the Siberian continental margin near the delta of the Lena River.

Until about 38 Ma, Spitsbergen and north-

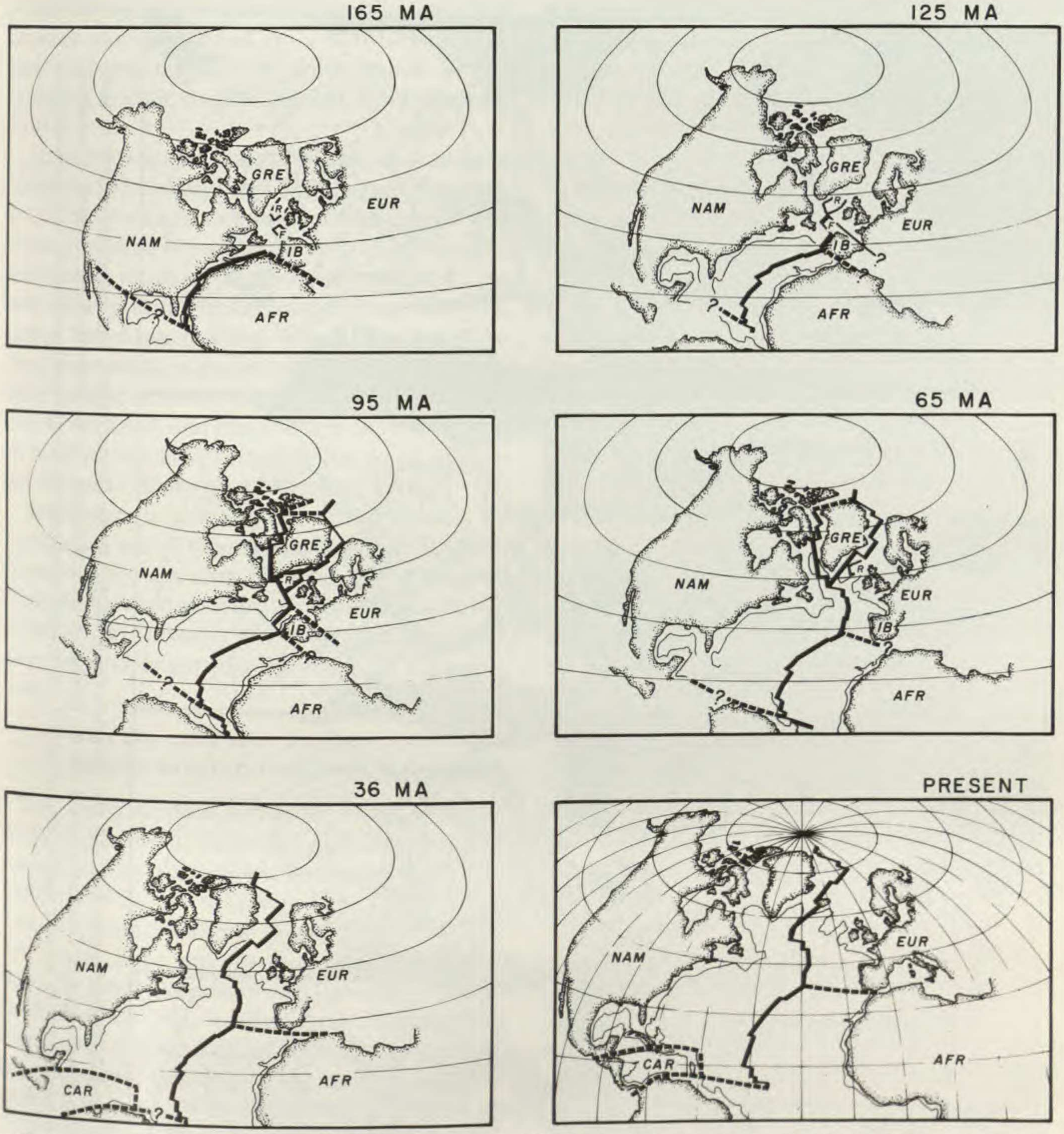

FIGURE 1. Tectonic history of the North Atlantic Ocean, showing positions of continental masses from Middle Jurassic time (165 Ma) through Early and middle Cretaceous (125 and 95 Ma), Cretaceous-Tertiary boundary time (65 Ma), and early Oligocene (36 Ma). NAM, GRE, EUR, CAR, IB, AFR, F, and R represent respectively North America, Greenland, Eurasia, Caribbean, Iberia, Africa, Flemish Cap plus Orphan Knoll, and Rockall Bank. The 2,000 m bathymetric contour around each continent is shown with a light line; heavy lines represent active spreading centers; dashed lines represent plate boundaries of unspecified types. Reproduced, with permission, from Sclater, Hellinger and Tapscott (1977, fig. 3), Journal of Geology, v. 85, p. 517, copyright by University of Chicago.

east Greenland were sliding past one another on a transform fault trending north-northwestward, and continental crust was continuous between them (Talwani & Eldholm, 1977; Vogt, Bernero et al., 1981, fig. 2). That this slip had a small compressive component is shown by the Paleogene deformation of southwest Spitsbergen. At about 38 Ma, the slow spreading between Greenland and North America ceased, the motion of Greenland became northwestward relative to Norway, and oblique extension began between Greenland and Spitsbergen; the result was

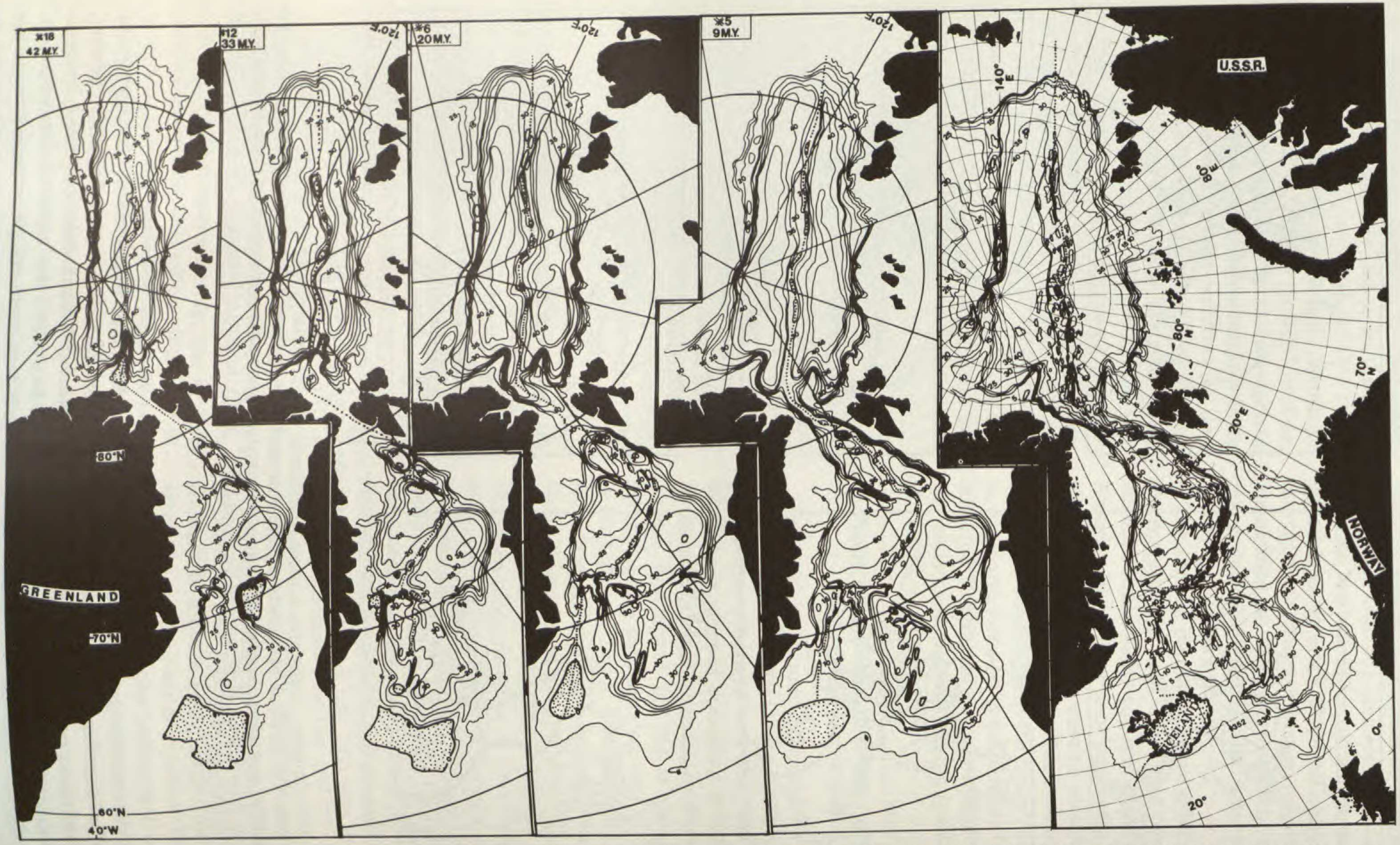

FIGURE 2. Present bathymetry of the Greenland-Norwegian Sea and the Eurasian Basin of the Arctic Ocean (right), and paleobathymetry in late Eocene, middle Oligocene, and early and late Miocene times. Contour interval 500 m, labeled in 100s of meters. Derived by matching magnetic anomalies of the indicated numbers and ages, and integrating with known age/depth curves for subsidence of oceanic lithosphere. Reproduced, with permission, from Vogt, Bernero, Kovacs and Taylor (1981, fig. 5).

a shallow seaway on thinned continental crust between them, followed by a narrow but deep and widening oceanic rift from about 30 Ma (Talwani & Eldholm, 1977; Vogt, Bernero et al., 1981).

Land connections. Dry land thus could have connected Greenland and Spitsbergen throughout Cretaceous and early Paleocene time (before most spreading occurred in the Arctic Atlantic) and during much or all of the rest of Paleocene and Eocene time (while continent-against-continent transform faulting was underway). Further, great basalt plateaus were built during Tertiary time on oceanic crust between Scotland and East Greenland, and these might have provided an intermittent land bridge before some time in the Miocene (Eldholm & Thiede, 1980).

Spitsbergen is now separated from Norway by the shallow sea of the continental Barents Shelf. Seismic-reflection data indicate that the strata beneath this shelf are mostly of pre-Cenozoic age (Eldholm & Talwani, 1977), so the shelf may have been emergent during much of Cenozoic time.

BAFFIN BAY AND LABRADOR SEA

The early, western center of North Atlantic spreading between Labrador and Greenland is represented by the oceanic Labrador [Sea] and Baffin [Bay] Basins. Magnetic anomalies, drilling data, and seismic-reflection surveys indicate that new ocean floor was forming in the Labrador Basin between Greenland and Labrador by a little before 75 Ma, earlier Late Jurassic and Cretaceous motion having been accommodated by extensional thinning of the continental margins (Hinz et al., 1979; Johnson et al., 1982; Le Pichon et al., 1979; Srivastava, 1978). Southern Greenland moved relatively northeastward away from Labrador until about 60 Ma; then, the relative motion slowed and changed to about north-northeastward, and spreading accelerated between Norway and Greenland. Motion between Greenland and Labrador ceased about 38 Ma.

The history of the northern part of the rift, between Greenland and Baffin Island, is less well known. Baffin Basin is floored by oceanic crust; magnetic anomalies trending north-northwestward indicate sea-floor-spreading of possible Paleocene and Eocene age in the deep, central part of the basin (Jackson et al., 1979; Keen et al., 1974). A Late Cretaceous age can be extrapolated for the margins of the oceanic rift, and for extensional thinning and faulting of the continental shelves prior to complete rifting. Upper Cretaceous marine strata are present on the Baffin Island continental shelf (MacLean & Falconer, 1979).

If the Baffin Basin anomalies are identified correctly as of Paleogene age, then the width of Paleogene ocean formed between Greenland and North America changes little within the Labrador and Baffin Basins; the Euler pole of relative rotation is distant, and northeast-trending transform faults step spreading from one basin to the other through the Davis Strait region.

Reconstructions between Greenland and Canada are complicated by crustal extension and basaltic magmatism along the margins of Baffin Bay and the Labrador Sea. Continental margins are thinned by extension accompanying rifting, and wedges of strata that prograde across them maintain continental shelves. Something like half the width of the shelf and continental slope shallower than 2,000 m along a rifted continental margin may typically represent extension of continental crust. The uncertainties of such extension are quantitatively most important for reconstructions of narrow ocean basins, such as those of Baffin Bay and the Labrador Sea. These uncertainties are further complicated by new crust built of very thick lower Tertiary basalts of mantle origin, onshore and offshore of west-central Greenland between 68° and 73°N, and on easternmost Baffin Island and the shelf east of southeastern Baffin Island (Keen et al., 1974; see also Johnson et al., 1982). Davis Strait, between the Baffin and Labrador Basins, is only 500 to 1,000 m deep and has crustal characteristics of a basalt plateau (Keen et al., 1974).

The Late Cretaceous magnetic anomalies of the Labrador Basin indicate an Euler pole of relative rotation between Greenland and North America somewhere near Alaska, and from this it can be predicted that the amount of Cretaceous spreading should decrease northwestward through Baffin Bay. This prediction is not fulfilled: southeastern Baffin Bay is too narrow, even if much of the width of its flanking continental shelves be assumed to represent spreading. Other plate boundaries northwest of the Labrador Basin must accommodate some of the Cretaceous spreading. The problem is alleviated but not eliminated if the central Baffin Bay magnetic anomalies are partly of Cretaceous age. Interpretations developed here are illustrated by Figures 3 and 4.

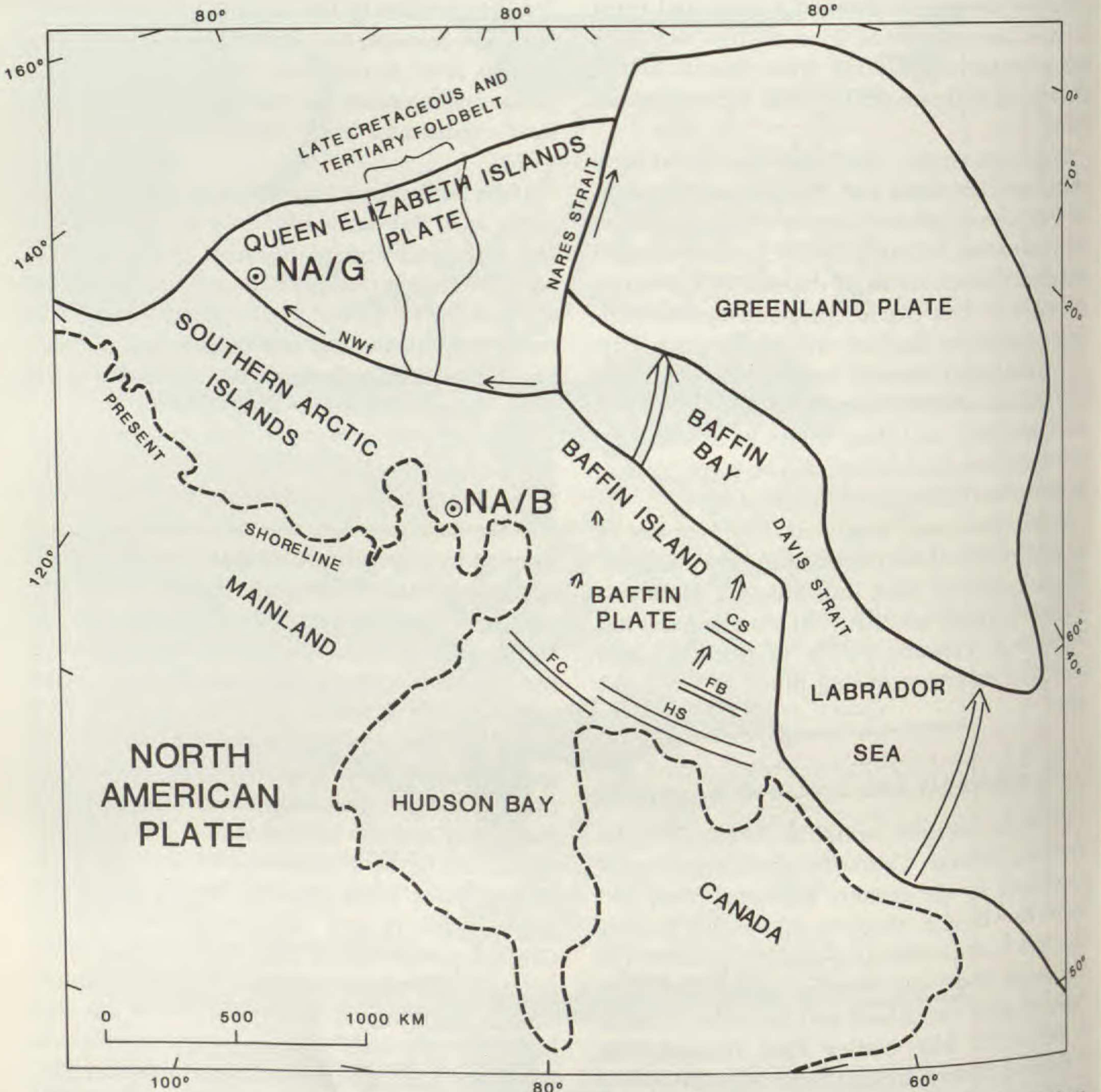

FIGURE 3. Schematic illustration of Cretaceous and Cenozoic plate motions inferred within the northern Canada-Greenland region; Atlantic and Arctic Ocean features are not included. Double arrows show overall motions relative to mainland Canada; single arrows show motions across strike-slip (transform) faults. Euler poles of relative rotation of plates shown by circles: NA/G, Greenland and mainland Canada; NA/B, Baffin Island and mainland Canada. Other abbrevations: CS, Cumberland Sound graben; FB, Frobisher Bay graben; FC, Fox Channel graben; HS, Hudson Strait graben; NWf, Northwest Passage fault. Reconstruction using these boundaries requires counterclockwise rotation of Nares Strait fault relative to Northwest Passage fault; the Tertiary foldbelt of the northern Arctic Islands is assumed to be the product of the resultant compression. Only the mainland Canadian shoreline is shown.

ROTATION OF BAFFIN ISLAND

Rotation of an internally fragmented Baffin Island lithosphere plate, counterclockwise relative to both Greenland and mainland North America, provides the likely explanation for much of the problematic geometry. Although Baffin Island generally has been assumed to be part of the rigid North American plate, its internal and marginal geology indicate otherwise (as Rice & Shade, 1982, recognized). Mainland Canada plus shallow Hudson Bay are separated from Baffin Island plus shallow Foxe Basin by the southeast-widening graben systems of Foxe Strait and Hudson Strait. These grabens contain Paleozoic strata in a region otherwise surfaced now mostly by Precambrian basement rocks (Sanford, 1974). Similar grabens containing Paleozoic strata form Frobisher Bay and Cumberland Bay, in eastern Baffin Island (MacLean & Falconer, 1979); young normal faults cross southern Baffin Island at least along the Frobisher Bay trend. Normal faulting requires crustal extension. The amount of faulting, and hence probably also of extension, decreases northwestward, so Baffin Island apparently has rotated counterclockwise relative to mainland Canada.

The Euler pole of that relative rotation might lie along the boundary between the Baffin and Canadian plates, in which case crustal compression should exist beween the plates along their boundary to the north of that pole, or the Euler pole might lie beyond the north limit of the boundary (here taken to be the Northwest Passage fault), in which case the boundary should be entirely extensional. Published geologic data appear to permit either interpretation. Cambrian to lower Tertiary strata are broken by numerous faults and monoclines, mostly trending northwestward, in northern Baffin Island and adjacent areas. Although the faults have been termed normal by all geologists who have mapped them, the strata of the downdropped sides rise toward some of the faults in moderately-dipping monoclines. Thus, the Eclipse trough, which contains 3 km of exposed middle Cretaceous to lower Eocene fill, and probably contains more beneath its submarine portion, has a marginal monocline, with basinward dips of as much as 40°, along its faulted northeast boundary (Jackson & Davidson, 1975; Miall et al., 1980). This geometry, and the presence of open folds away from faults, permit the inference that the Cenozoic deformation is compressional, rather than extensional, in this northern region. (I have seen no statements regarding actual observations of dips of Cenozoic faults.) Further, some of the compressive deformation of the Boothia uplift, west of northern Baffin Island, is possibly of Cretaceous or early Cenozoic age. The straightness and continuity of some of the Phanerozoic faults (e.g., Blackadar et al., 1968) of west-central Baffin Island, however, permit an inference of dominantly strike-slip faulting there.

Cretaceous and Paleogene extension on the order of 100 km might reasonably have produced the normal faulting in the southeast Baffin region. (Rice & Shade, 1982, suggested 80 km.) An Euler pole in the region of 69°N, 86°W, near Melville Peninsula, would account for the normal faulting of the southeastern Baffin region by orthogonal extension; for strike-slip faulting in west-central Baffin Island; and for crustal shortening in northern Baffin Island and any young component of shortening in the Boothia uplift—*if* these disparate elements are all of the same age and are characterized correctly in this scenario. Adoption of such an Euler pole, plus the assumption of 100 km of extension in the southeast, would predict about 5° of rotation, and hence about 70 km of total crustal shortening between northeast Baffin Island and the mainland west of the Boothia uplift. If, however, the Boothia compression is entirely older, and the north Baffin structures are extensional rather than compressional, then the Euler pole lies farther northwest, beyond the Northwest Passage. Such a pole would require a smaller angular rotation of the Baffin plate. Either interpretation can be inte-

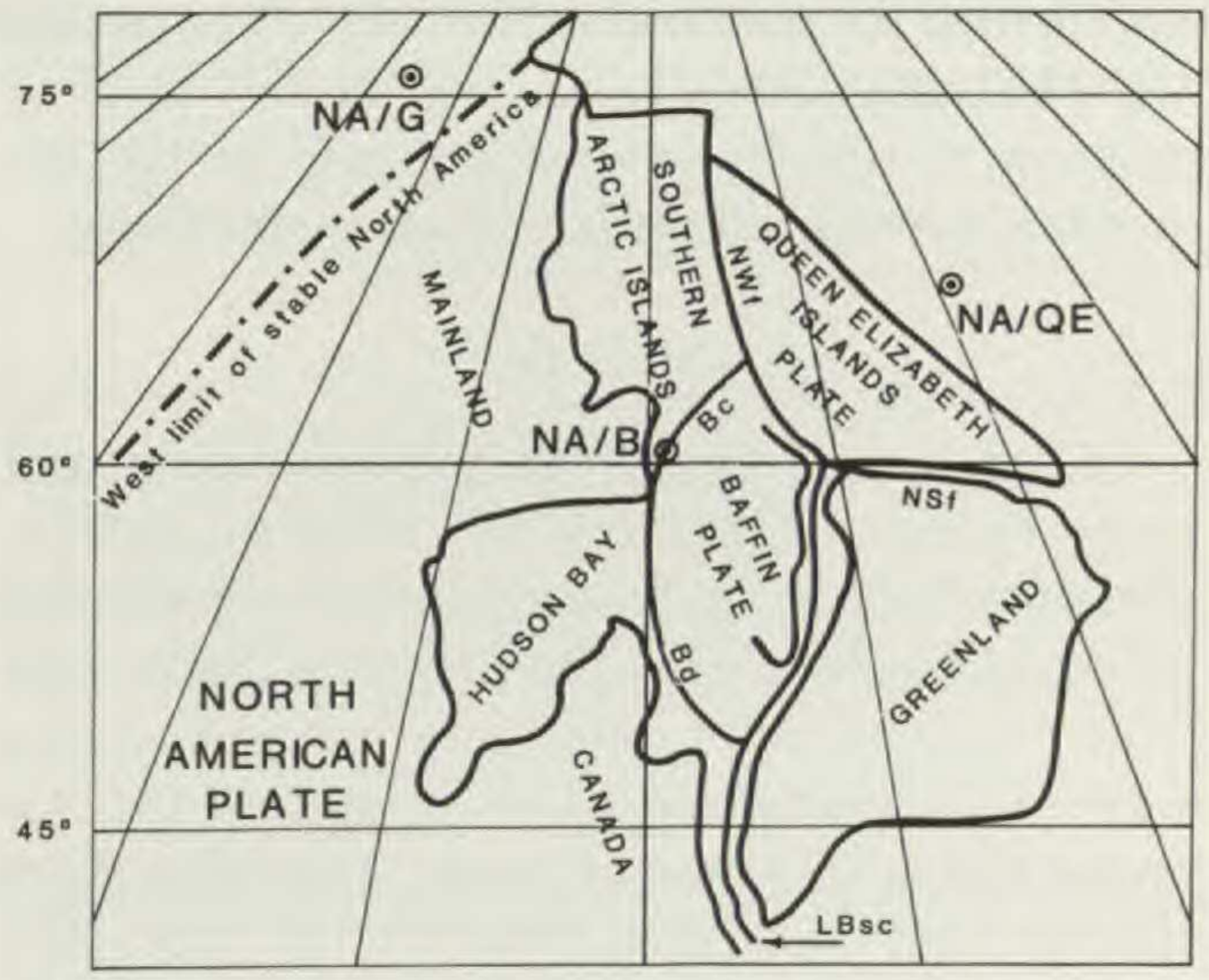

FIGURE 4. Reconstruction of Greenland and northeast Canada in middle Cretaceous time. Present shorelines of mainland Canada, northeastern Baffin Island, and Greenland are shown; boundaries of Arctic-island groups are generalized. The paleolatitudes correspond to a North American paleomagnetic pole position of 68°N, 173°W, after the compilation by Van der Voo (1981). Longitude lines are 15° apart and illustrate the equal-area projection. Plate boundaries marked by heavy lines: LBsc, Labrador Basin-Baffin Basin spreading center; NWf, Northwest Passage transform fault; NSf, Nares Strait transform fault; Bc and Bd, convergent and divergent parts, respectively, of boundary between Baffin Island and North American plates. Circles show Euler poles of subsequent relative rotations of plates: NA/G, North America and Greenland; NA/B, North America and Baffin Island plate; NA/QE, North America and Queen Elizabeth Islands plate. Arctic and Atlantic Ocean features, and Eurasian, Alaskan, and Cordilleran landmasses, are not depicted.

grated with the motions defined for the opening of the Labrador Basin to account for the observed progressive northwestward decrease in the net motion between Baffin Island and Greenland.

SEAWAY

The history of rifting, oceanic circulation, and paleoclimates was deduced by Gradstein and Srivastava (1980) by study of microfossils from wells on the shelves flanking the Labrador Basin, and from two deep-water wells in the basin. A seaway west of Greenland probably connected the Atlantic and Arctic Oceans most of the time from the late Late Cretaceous (Maestrichtian) on. The Northwest Passage may have been the main early channelway between Baffin Bay and the Arctic Ocean. In the Maestrichtian, and again in the early and early middle Eocene, subtropical Gulf Stream waters reached about as far north as present latitude 50°N (paleolatitude about 35° or 38°); water was cooler during the Paleocene and again during the middle Tertiary, but there probably was a general northward flow of water toward a nonglacial Arctic Ocean. By late Miocene time, the cold, south-flowing Labrador Current was in existence and glacial conditions presumably existed in the Arctic.

TRIPLE JUNCTION AT THE NORTH END OF BAFFIN BAY

The 450 km or so of spreading of northern Baffin Bay represents plate motions that could not have stopped at the north end of the bay, and that must have been accommodated on other plate boundaries to the north of Baffin Island and Greenland. The various proposals for these boundaries in the literature include a ridge-transform junction, a ridge-ridge-ridge triple junction, a ridge-trench junction, a pivot between spreading and compression, and rejection of plate tectonic concepts. None of these proposals fits both the geometric requirements and the known geologic and geophysical parameters, and I do not discuss them here. Instead, I note evidence of a triple junction between the Baffin Bay spreading center and two left-slip transform faults. One of these faults follows narrow Nares Strait north-northeastward from the north end of Baffin Bay, separating Greenland and Ellesmere Island. The other fault trends westward from the north end of Baffin Bay, along the aligned straits of the Northwest Passage. Fault, fault, and spreading center meet at mutual angles of about 120°. Neither fault is itself in a transform (small-circle) relationship to any likely spreading direction between Greenland and Canada; but by postulating simultaneous motion on both faults, the separation of Greenland from mainland Canada can be reconciled with Arctic geology.

Nares Strait fault. The linear trend of Nares Strait north-northeast from the head of Baffin Bay, between Ellesmere Island and Greenland, continues beyond Ellesmere as the north edge of the submerged continental margin of North Greenland (Figs. 3 and 5). The strait was assumed by Wegener (1920), and by most subsequent investigators of continental drift and, later, of plate tectonics, to mark a strike-slip fault having about 250 km of left slip, related to the opening of Baffin Bay.

I believe that such a fault does indeed exist. Many geologists disagree. A symposium on evidence for and against the fault was convened in 1980, and its results were published in a volume edited by Dawes and Kerr (1982). In general, symposium authors concerned with plate reconstructions showed that no geometric alternative to a strike-slip fault has been recognized, whereas most of the geologists familiar with the geology on one side or the other of the strait argued for little or no faulting. The latter group collectively presented an impressive number of arguments against major faulting by projecting geologic zones and lines across the strait with little or no offset, as summarized by Dawes and Kerr in the final paper in the book. Having examined the primary geologic literature on both sides of the strait—reconnaissance 1:250,000 geologic maps and various reports and monographs for Ellesmere, more limited materials for Greenland—I regard none of the anti-fault arguments as proved and, hence, regard their sum also as unconvincing.

The critical components at issue are lines representing changes in sedimentary facies and style of deformation in Paleozoic strata on both sides of the strait. Some such lines are drawn without offset across the strait by the anti-fault geologists but are unconstrained on one side or the other, and hence are irrelevant. Others could be constrained by data on both sides but instead appear to be drawn schematically where they might cross the strait, if indeed there were no faulting, not where the data placed them independently. On the contrary, the front of deformation in Paleozoic strata, the hinge line between platform and continental shelf Paleozoic strata, the outer limit of shelf strata, and various other elements appear

FIGURE 5. Bathymetry of the Arctic Ocean. Contour interval 1 km, with an additional contour at 0.5 km. Reproduced, with permission, from Taylor, Kovacs, Vogt and Johnson (1981, fig. 1a).

to me to accord with left slip of about 250 km along the strait, just as Wegener inferred long ago.

Nares Strait approximates a segment of a great circle. It is not a small circle to any likely Euler pole of relative rotation between Greenland and Canada, and hence must have changed in shape, position, or orientation relative to spreading centers between Greenland and Canada as spreading progressed.

Northwest Passage fault. The aligned sounds, 50 to 100 km wide, of the Northwest Passage curve westward from the north end of Baffin Bay and separate the northern and southern islands of the Canadian Arctic Archipelago. The midline of these sounds approximates a small circle to a pole near 85°N, 95°W, so the passage may mark a strike-slip fault along which the northern islands have slipped relative to the rest of Canada. Published data on distribution of facies in the widespread Paleozoic platform strata are compatible with a left slip of as much as 200 km, but not with any right slip (cf. Daae & Rutgers, 1975, and Kerr, 1980; these authors, however, assumed zero strike slip). Longitudinal faulting and variably thick Cretaceous and Paleogene sedimentation in the passage are shown by geophysical data (Daae & Rutgers, 1975), and extensional faulting (which I assume to be oblique) is indicated in the eastern sector (Kerr, 1980).

Kerr (1974, 1977) argued against young strike-slip faulting along the Northwest Passage because the compressional "Cornwallis foldbelt" trends directly across the passage and is of Devonian age. Although structures north and south of the passage are indeed approximately in line, I interpret the geologic maps of Bathurst and Cornwallis Islands (Kerr, 1974; Thorsteinsson & Kerr, 1968), north of the passage, to indicate that the structures there are in fact of Tertiary age, and hence do not constrain strike-slip faulting. For example, a tract of uppermost Cretaceous and lower Tertiary strata on Cornwallis Island (the "Intrepid Bay Graben" of Thorsteinsson & Kerr, 1968, who regarded the Tertiary deformation as extensional) consists of an asymmetric syncline of the young rocks, against the steep, west limb of which is faulted a complex anticline of lower Paleozoic strata. Such geometry characterizes compressional, not extensional, structures.

South of the Northwest Passage, north-trending compressional faults of the Boothia uplift break basement as well as cover rocks, and can be dated directly only as postdating Lower Devonian strata and as predating highest Cretaceous strata (e.g., Miall & Kerr, 1977). That an upland was growing within the belt in mid Paleozoic time is indicated, however, by coarse clastic Upper Silurian and Lower Devonian sediments shed from it both to east and west (Miall & Gibling, 1978). No analogous upland is shown by correlative strata north of the passage, where dominantly carbonate rocks accumulated during this stratigraphic interval, platform conditions to the southeast giving way northwestward to continental-shelf ones. The lack of present continuity may be a result of post-Devonian faulting along the Northwest Passage, and the anticipated northern continuation of the upland and derivative clastics may now be hidden beneath younger strata and the sea farther west.

RECONSTRUCTION OF CANADA AND GREENLAND

If Baffin Island be rotated back to its pre-Cretaceous position as proposed previously, and southern West Greenland be brought back against Labrador in accord with the well-constrained magnetic-anomaly patterns of the Labrador Basin, the northern part of West Greenland is brought against Baffin Island in a reasonable fit (Fig. 4). The total motion of the south tip of Greenland, relative to mainland Canada, that is indicated by this reconstruction is about 800 km in northeastward direction. The motion reversed corresponds to a counterclockwise rotation of about 9° of Greenland relative to mainland Canada, about an Euler pole near 65°N, 140°W in a Canadian reference frame.

This reconstruction of Greenland, Baffin Island, and Canada is possible only if there is left slip on both Nares Strait and Northwest Passage faults. The specific reconstruction requires about 300 km of left slip through Nares Strait (compared to the best geologic value of about 250 km), and about 200 km of left slip along the Northwest Passage. The reconstruction also requires that the Northwest Passage and Nares Strait fault boundaries of the northern Arctic Islands (Queen Elizabeth Islands) have rotated toward one another about 5°, about the point of their intersection; the predicted northwest-increasing crustal shortening is presumed to be taken up by the northwest-widening belt of Cretaceous and early Tertiary folding in the islands.

TECTONICS OF THE ALASKAN REGION

The west limit of continental crust, as defined by the presence of continental-shelf strata and by other criteria, that was part of North America in early and middle Paleozoic time trends northwestward in interior British Columbia and southern Yukon, thence northward through northern Yukon to the Arctic Ocean. All land now to the west of this, including nearly all of Alaska, probably was added tectonically to the continent during Devonian and younger time. Diverse rotations and strike-slip motions have accompanied the tectonic accretion. The complexity of the collage increases northwestward, and comprehension of its evolution decreases correspondingly (e.g., Jones & Silberling, 1979; Jones et al., 1982; Monger et al., 1982; Tipper et al., 1981). A large part of the collage was assembled (although with grossly different configuration than it has now) before the middle of Cretaceous time. I will treat it here in only cursory fashion.

OPENING OF THE CANADA BASIN

The oceanic Canada Basin, north of Alaska and western Canada (Fig. 5), was formed by Mesozoic spreading, although the specific geometry and timing of that spreading are poorly constrained. Interpretations have varied widely in detail but in general have advocated either that northern Alaska rotated counterclockwise away from Arctic Canada, as though about a pivot in the Mackenzie Delta region (e.g., Grantz et al., 1979), or that much of Alaska slid southwestward past Arctic Canada, the ocean opening behind it (e.g., Norris & Yorath, 1981). I strongly favor the rotation option. Magnetic-anomaly patterns of the Canada Basin are irregular (unlike the tidy, symmetrical anomalies of the Eurasia Basin; Fig. 6), and can at the present level of knowledge be fitted to either rotation or sliding models (Vogt et al., 1982). The onshore and offshore geology and geophysics of northern Alaska and northwestern Canada indicate that rifting premonitory to opening of the Canada Basin had begun by Early Jurassic time, and that an ocean of undefined width was present at least as early as late Early Cretaceous time (e.g., Grantz et al., 1979; Miall, 1979; Young et al., 1976). The magnetic anomalies of the basin were inferred by Vogt et al. (1982) to date the ocean floor as having formed largely within Late Jurassic and Early Cretaceous time.

The Canada Basin apparently is largely or entirely older than the Late Cretaceous and Cenozoic spreading and transform faulting by which the Eurasia Basin, Arctic Atlantic, Labrador Sea, and Baffin Bay were opened.

FIGURE 6. Magnetic anomalies of the Arctic Ocean and the northern Greenland-Norwegian Sea, showing medium-length anomalies greater than (black) and less than (white) the global magnetic reference field. The discontinuity near 160°W–60°E presents different data-reduction methods for the Soviet data, on the Eurasian side, and the generally more detailed U.S. Navy and Canadian data. Reproduced, with permission, from Vogt, Bernero, Kovacs and Taylor (1981, fig. 2).

ROTATION OF NORTHERN ALASKA

The Paleozoic and early Mesozoic geology of northern Alaska—the Brooks Range and North Slope—and adjacent northern Yukon Territory (e.g., Dillon et al., 1980; Grantz et al., 1979; Norris & Yorath, 1981) is compatible with the morphologically reasonable rotation of that region 65° counterclockwise away from the Canadian Arctic Islands (cf. Grantz et al., 1979). In the latter region, three major tectonic and lithologic or stratigraphic terranes trend generally west-southwestward to westward in the Queen Elizabeth Islands to oblique truncations against the margin of the Canada Basin. Analogous terranes in northern Alaska can be explained as rotated sectors of the same terranes. One assemblage consists of Mississippian through lower Mesozoic strata (in the Canadian Arctic, the Sverdrup Basin fill) lying unconformably on older complexes. The other two shared assemblages are pre-Mississippian. The southern one in the Canadian Arctic is a tract about 150 km wide of contorted and low-grade-metamorphosed upper Precambrian(?) through Silurian deep-water strata (e.g., Trettin et al., 1979). This terrane lies north of the continental-shelf assemblage of correlative shallow-water materials, deposited on North American crust. I interpret the deep-water materials to be sediments of the continental slope, continental rise, and abyssal plain, crumpled together while oceanic lithosphere beneath them was being subducted beneath an advancing northern landmass in Devonian time. Analogous materials in the northern part of the Alaska-northwest Yukon region are exposed in the Romanzof and other uplifts and are known also in the subsurface along the north coast. The northern terrane in the Canadian Arctic is an assemblage of continental and oceanic crystalline and sedimentary rocks, of late Precambrian to Devonian ages (e.g., Trettin, 1982), which record poorly understood Devonian and older plate convergence and tectonic accretion. Equivalents of this northern Canadian Arctic assemblage appear to be represented by the Devonian and older terrane of the southern Brooks Range and nearby Yukon Territory.

CENTRAL AND SOUTHERN ALASKA

Alaska south of the Brooks Range consists of diverse terranes, some crustally oceanic and some continental, that have moved long distances with regard to the Brooks Range, mainland North America, and each other. The terranes are variously of Paleozoic, Mesozoic, and Cenozoic ages, but their present juxtapositions and configurations are primarily products of Cretaceous and Cenozoic subduction, strike-slip faulting, and oroclinal folding. Many terranes, sutures, and magmatic arcs have been identified, with varying levels of confidence, and fragmentary histories deduced; but any attempt at statewide palinspastic reconstructions for Cretaceous and early Paleogene configurations could be at present only quite speculative.

A large part of central and southern Alaska was nevertheless structurally part of North America by Late Cretaceous time. The suturing of the large Yukon-Koyukuk terrane, apparently an oceanic island arc, to the south edge of the Brooks Range occurred late in Early Cretaceous time. Before then, various terranes now farther south in Alaska were attached to the continent, but at positions farther southeast along the Cordillera; they slid northwestward to their present positions to form an increasingly wide Alaska.

The Aleutian Trench marks the present south margin of the Alaskan plate. Pacific oceanic lithosphere is moving relatively northwestward and subducting beneath Alaska and the Bering Sea. Alaska is widening as oceanic materials are scraped off into the accretionary wedge at its leading edge.

Tectonics of Northeastern Eurasia

The northern part of mainland Eurasia west of present latitude 162°E was assembled by the end of Jurassic time, although both major internal deformation and tectonic accretion continued in the east during the Cretaceous and Cenozoic (Churkin & Trexler, 1979; Dickinson, 1978; Fujita & Newberry, 1983; Hamilton, 1970; Takahashi, 1983; Tapponnier & Molnar, 1979[2]). It is likely that since about the middle of Cretaceous time, continuous crust of continental thickness (and hence, at least intermittently dry land) has joined mainland Eurasia and North America via the region of northeastern USSR and Alaska, although much doubt clouds specific palinspastic restorations.

PACIFIC MARGIN

Kamchatka Peninsula, the Koryak Highlands to the northeast of it, and the region northwest of the Koryaks, consist of a complex collage of accretionary and magmatic-arc terranes, 700 km wide, assembled primarily by Cretaceous and Cenozoic plate convergence. Subduction northwestward beneath the continent apparently began early in Cretaceous time, for Lower and Upper Cretaceous arc-magmatic rocks lie across the truncated and poorly understood components of older Mesozoic mainland terranes west of the Koryaks. Jurassic and Cretaceous fossils occur sparsely in the accretionary-wedge melanges that are widespread across most of the width of the collage; terranes of lower to upper Paleozoic rocks include fossils so foreign paleoclimatically to mainland northeast Asia as to require subduction of many thousands of kilometers of intervening oceanic lithosphere. Seamount and island-arc terranes are recognizable in the fragmentary Soviet descriptions, aided by analogy with northwestern North America. Melanges and Cretaceous and early Paleogene magmatic-arc rocks tend to become younger toward the Pacific, indicating a general sequence of tectonic accretion in that direction. Middle and upper Paleozoic components of mega-melange, including fragments of seamounts and atolls, are widespread in the Pacific half of the Koryak region, and as it is unlikely that any seafloor of this age

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[2] Plate-tectonic interpretations of Soviet geology have come primarily from outside the Soviet Union, because plate concepts are all but lacking in the USSR. The papers cited above give references to Soviet publications. The following brief discussion is adapted from the references cited above and from my own reading of the Soviet literature regarding the far northeastern USSR.

was still unsubducted in Late Cretaceous time, tectonic assembly elsewhere is likely.

The Cretaceous magmatic arc of the Asian mainland margin, analogous to that west of the Koryak region, is present in Sikhote Alin, and the matching accretionary terrane is in Sakhalin, far west of the middle and late Cenozoic Hokkaido-Kuril-Kamchatka arc system. Dickinson (1978) inferred from regional geologic and geophysical relationships that a small continental crustal mass, represented now by the shallow part of the Sea of Okhotsk and perhaps by exposures in western Kamchatka, collided with the continental-margin subduction system in about Eocene time, and that subduction then broke through on the Pacific side of that added mass. Migration of the arc systems, and the opening of the Sea of Japan and the deep-water part of the Sea of Okhotsk, has occurred since.

ARCTIC MARGIN

The modern spreading center of the Nansen-Gakkel Ridge trends south-southeastward to the north edge of Eurasia, north of the Lena River delta (Figs. 5 and 6). The amount of Late Cretaceous and Cenozoic spreading decreases toward Eurasia but is still about 600 km at the Eurasian continental slope. One or several plate boundaries must connect this spreading center to past and present plate boundaries around the Pacific Ocean. A zone of diffuse seismicity continuing southeastward through the Lena River region to the Sea of Okhotsk presumably represents the modern boundary along which extension decreases southeastward between Eurasian and North American plates (Chapman & Solomon, 1976). Spreading within the region of the seismic zone cannot be great enough, however, to account for more than a small part of the total motion needed, for this mainland region is topographically high and is not conspicuously rifted.

One or more other plate boundaries, distinct or diffuse and now inactive seismically, must lie within the onshore or offshore region of Arctic Siberia. The most conspicuous geologic boundary onshore in the region is that trending east-southwestward relative to mainland Eurasia. Alternatively, perhaps, the broad lowlands of Arctic Siberia, undergoing active sedimentation between the Lena River and about 160°E, mark a zone of distributed crustal extension, offset from the modern seismic zone (cf. Chapman & Solomon, 1976).

BERING SEA REGION

The crust beneath the deep southwestern half of the Bering Sea, inside the Aleutian island arc, is oceanic, but that of the northeastern half is of continental thickness. Although now covered by shallow water, much of this latter half undoubtedly stood above sea level during much of its history.

Two broad geologic provinces can be recognized from geophysical and geologic data from the Bering Sea continental shelf and its margins. In the north, the terrane that includes the Brooks Range of northern Alaska inflects southward to form the Seward Peninsula of northwest Alaska, and thence trends westward through St. Lawrence Island to northeastern Chukotsk Peninsula (e.g., Patton & Tailleur, 1977). In the south is the broad terrane of accretionary geology and magmatic arcs connecting southwest Alaska and the northeast Koryak-southwest Chukotka region, probably consolidated mostly in Cretaceous and early Paleogene time (Csetjey et al., 1971; Marlow et al., 1976; Moore, 1972; Patton et al., 1976; Pratt et al., 1972). The accretionary and arc-magmatic history of the present shelf region ended in latest Cretaceous or very early Tertiary time, when subduction northward beneath the shelf region ceased.

The modern boundary between the Pacific and North American plates south of the Bering Sea is the Aleutian trench, which curves from southwest mainland Alaska to a trench-trench junction off Kamchatka. The Aleutian island arc has been active only since early or middle Eocene time; oceanic lithosphere between the Aleutians and the Bering continental slope probably is a trapped bit of Mesozoic ocean floor (Cooper et al., 1977) but might instead have formed in early Cenozoic time behind migrating island arcs (Langseth et al., 1980). Curving from the north side of the central Aleutian arc to the Koryak region are the Bowers and Shirshov submarine ridges—segments of a fossil arc beneath which subduction was southward (Cooper et al., 1981). Various explanations (e.g., Ben-Avraham & Cooper, 1981) have been proposed for the evolution of this complex submarine region. The most promising is one communicated to me by Dan M. Worrall, who integrated offshore geophysical data with onshore geological information. Worrall inferred that a northward-migrating, north-facing Bowers-Shirshov island arc collided with a south-facing Bering-Koryak Highlands continent-margin trench system in early Eocene time. He also inferred that both of these systems were abandoned when the Aleutian subduction system broke through the oceanic plate to the south, trapping Mesozoic oceanic crust to the north of it.

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